**Astronomy
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Astrophysics**

Correlated Infrared and X-ray variability of the transient Anomalous X-ray Pulsar XTE J1810-197[★]

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Abstract. We report on observations aimed at searching for flux variations from the proposed IR counterpart of the Anomalous X-ray Pulsar (AXP) XTE J1810−197. These data, obtained in March 2004 with the adaptive optics camera NAOS-CONICA at the ESO VLT, show that the candidate proposed by Israel et al. (2004a, ApJ, 603, L97) was fainter by $\Delta H = 0.7 \pm 0.2$ and $\Delta K_{\rm s} = 0.5 \pm 0.1$ with respect to October 2003, confirming it as the IR counterpart of XTE J1810−197. We also report on an XMM-Newton observation carried out the day before the VLT observations. The $0.5-10$ keV absorbed flux of the source was 2.2×10^{-11} erg cm^{-2} s^{-1}, which is less by a factor of about two compared to the previous XMM-Newton observation on September 2003. Therefore, we conclude that a similar flux decrease took place in the X-ray and IR bands. We briefly discuss these results in the framework of the proposed mechanism(s) responsible for the IR variable emission of AXPs.

Key words. stars: pulsars: individual: XTE J1810−197 – stars: neutron – X-rays: stars

1. Introduction

The X-ray source XTE J1810−197 was discovered in July 2003 as a transient pulsar with a flux of $\sim 5 \times 10^{-11}$ erg cm^{-2} s^{-1} and a period of 5.5 s (Ibrahim et al. 2004; Markwardt et al. 2003). Already from the first RXTE and *Chandra* results it clearly appeared that the properties of XTE J1810−197 are different from those of the majority of X-ray transient pulsars. The latter are easily identified as neutron stars accreting from companion stars. On the other hand the long term spin-down at $\sim 10^{-11}$ s s^{-1}, the soft X-ray spectrum, and the upper limits on its optical counterparts indicated XTE J1810−197 as a likely member of the class of Anomalous X-ray Pulsars (AXPs, see Mereghetti et al. 2002 and Woods & Thompson 2004, for a review). The AXP nature of XTE J1810−197 was further strengthened by an XMM-Newton observation

(Tiengo & Mereghetti 2003; Gotthelf et al. 2004) showing the blackbody plus power law spectrum typical of this class of sources, as well as by the identification of a candidate IR counterpart with $K_{\rm s} \sim 20$ (Israel et al. 2004a).

The AXP constitute an enigmatic class of pulsars, most likely hosting young neutron stars, which has attracted increasing interest since its first recognition (Mereghetti & Stella 1995; van Paradijs et al. 1995). The rotational energy loss inferred from their spin-down, assuming they are neutron stars, is insufficient to power their X-ray luminosity of $\sim 10^{34}-10^{35}$ erg s^{-1}, and they lack evidence of companion stars which could power the emission through mass accretion. Similarities with the persistent X-ray counterparts of the Soft Gamma-ray Repeaters (e.g., Hurley 2000; Woods & Thompson 2004) led to the speculation that the AXP might be powered by the decay of strong magnetic fields (Duncan & Thompson 1992; Thompson & Duncan 1995). Recent observations of bursts from the AXPs 1E 2259+586 and 1E 1048.1−5937 and

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support this "Magnetar" model (Kaspi et al. 2003; Gavriil et al. 2002; Kaspi et al. 2004), but also other scenarios are discussed by several authors and not completely ruled out. For example several models based on accretion from residual disks around isolated neutron stars have been proposed (Alpar 2001; Perna et al. 2000; Chatterjee et al. 2000).

The particular interest for XTE J1810−197 lies in its transient nature, as testified by archival observations showing a luminosity a factor ∼100 below that observed in 2003−2004. In fact, most AXP have shown until recently little or no long term variability[1].

The results on XTE J1810−197 imply the existence of a, possibly large, population of quiescent AXPs in the Galaxy, with relevant implications on the nature and evolution of these objects. Recent observations have also revealed variations in the X-ray flux of a few "persistent" AXPs (Kaspi et al. 2003; Mereghetti et al. 2004; Gavriil & Kaspi 2004), as well as in their infrared counterparts (see Israel et al. 2004b). However, a clear picture of these variability properties has still to emerge. In this context, multi-wavelength monitoring of XTE J1810−197, the only confirmed transient AXP, can yield interesting results. Here we report on nearly simultaneous X-ray and IR observations of XTE J1810−197, showing a flux decrease in both bands which confirms the proposed IR identification.

2. Data analysis and results

Deep IR imaging was obtained at the VLT-UT4 Yepun with the Nasmith Adaptive Optics System and the High Resolution Near IR Camera (NAOS-CONICA) on 2004 March 12–14. The pixel size of the camera is 0.027″. Images were reduced with the instrument-specific pipelines and checked by reducing them again with the software package *eclipse*. A total of 18 cube images in Ks and 26 in H, of 40 s exposure each, were obtained, for a total exposure time of 36 and 52 min in Ks and H, respectively. The on-axis *FWHM* was determined to be 0.09″ (3.3 pixels) in K_s and 0.10″ (3.6 pixels) in H.

Aperture photometry was performed with the *digiphot* package of IRAF[2]. The two output catalogues were matched and calibrated by using a set of secondary standards in the field, for which magnitudes and colours were already obtained in October 2003 (Israel et al. 2004a). We found the following IR magnitudes for the proposed IR counterpart: K_s = 21.36 ± 0.07 and H = 22.73 ± 0.18. The object was not detected in the J band (J > 23.0, 3σ u.l.). The corresponding values in October 2003 were K_s = 20.8 ± 0.1 and H = 22.0 ± 0.1.

As shown in Fig. 1, where the difference between the magnitudes in October 2003 and March 2004 are plotted for all the objects within ∼7″ from the Chandra AXP position, only the proposed IR counterpart to XTE J1810−197 showed a significant variation, with ΔH = 0.7 ± 0.2 and ΔK_s = 0.5 ± 0.1.

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[1] The only exception being AX J1844−0258 (Gotthelf et al. 2001), which is actually a "candidate" AXP, detected only once and for which a period derivative measurement is still lacking.

[2] Task *phot* in the *daophot* package (Stetson 1990), and corrected for aperture at infinity with the *mkapfile* routine available in the package *photcal*.
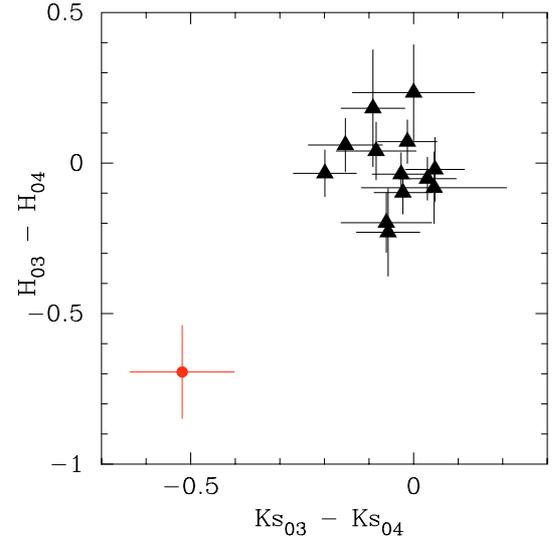

Fig. 1. VLT NAOS–CONICA H and K_s band magnitude differences between October 2003 and March 2004 observations obtained for all the objects detected within a circular region of about 7″ radius from the Chandra position (Israel et al. 2004a). Filled circle represents the XTE J1810−197 measurements, while filled triangles the differences for all the other stars.

XTE J1810−197 was observed with XMM-Newton for 16 ks on 11 March 2004. All the EPIC cameras were used with the medium thickness filter (Turner et al. 2001; Strüder et al. 2001). The MOS detector was in Small Window mode (time resolution 300 ms over a ∼1.5′ × 1.5′ field) while the PN was in Large Window Mode (time resolution 48 ms over a ∼13′ × 26′ field). Standard SAS 6.0 tools were used for the data reduction. Coherent pulsations at 5.53 s were detected with standard Fast Fourier algorithms and the best period value of P = 5.539917±0.000005 s (90% confidence level; at the epoch: 53 075.49196187 MJD) was obtained with phase fitting techniques. Compared with the period measured in the September 2003 XMM-Newton observation, this yields an average $\dot{P}$ = (3.6 ± 0.1) × 10^{-11} s s^{-1}. Comparing the frequency derivative reported for the RXTE data of XTE J1810−197 (Ibrahim et al. 2004) we found that a variation occurred in the period derivative, which is now greater by a factor of about three respect to the value reported for the July-September 2003 time span. The pulsed fraction (semiamplitude of modulation divided by the mean source count rate) in the 0.6–10 keV energy range was 49 ± 1%.

The source spectrum was extracted from a 32″ radius circle and the background from source free regions in the field. The spectrum was well fitted by a two component model composed of an absorbed blackbody plus a power law with N_H = 0.96 ± 0.03 ×10^{22} atoms cm^{-2}, kT = 0.67±0.01 keV and photon index of Γ = 3.8±0.1 (χ_ν^2 = 1.15; uncertainties are at 90% confidence level; see Fig. 2). The corresponding blackbody radius was 1.23 ± 0.02 km, for an assumed distance of 4 kpc (the estimated distance is 3–5 kpc; Gotthelf et al. 2004). The 0.5−10 keV absorbed flux was (2.2 ± 0.1) × 10^{-11} erg cm^{-2} s^{-1}, corresponding to an unabsorbed flux of 8.2 × 10^{-11} erg cm^{-2} s^{-1}. The blackbody component accounts for the 60% of the absorbed flux in the 0.5−10 keV band.
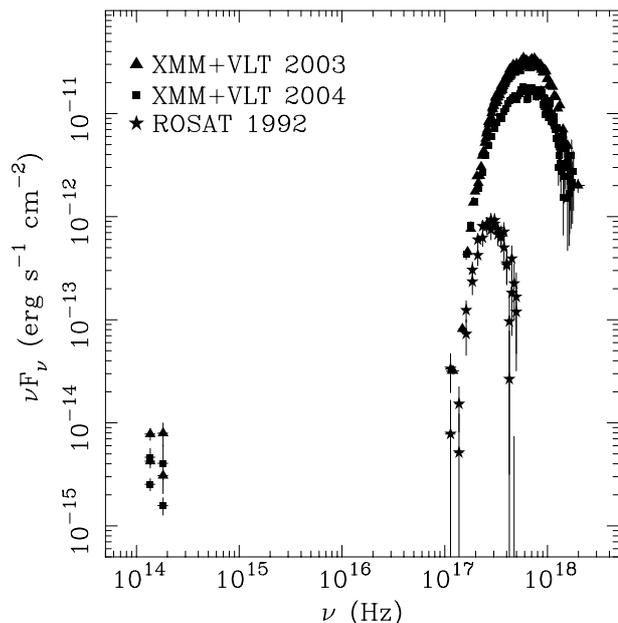
Fig. 2. Broadband energy spectrum of XTE J1810−197. Filled squares represent the 2004 XMM-Newton PN and VLT-NACO observations while triangles are relative to the 2003 observations. Moreover filled stars represent the spectrum of the ROSAT 1992 observation. Reported IR fluxes are absorbed and unabsorbed.

Fig. 3. Resulting correlation between X-ray and IR luminosity from a disk (assuming a typical 60 deg inclination of the disk and a distance of ~5 kpc).

An equally acceptable fit (χ^2_ν = 1.23) was also obtained keeping the absorption fixed at the September 2003 value (1.05×10^{22} atoms cm^{-2}; Tiengo & Mereghetti 2003, Gotthelf et al. 2004). The resulting spectral parameters were kT = 0.68 ± 0.01 keV and Γ = 4.1 ± 0.1.

Using two blackbodies to fit the spectra we found: N_H = $0.58 \pm 0.02 \times 10^{22}$ atoms cm^{-2}, kT_1 = 0.29 ± 0.01 keV (radius of 5.1 ± 0.6 km) and kT_2 = 0.70 ± 0.01 keV (radius of 1.21 ± 0.04 km; χ^2_ν = 1.17). The first blackbody had a $0.5-10$ keV absorbed flux of 3.9×10^{-12} erg cm^{-2} s^{-1} (18% of the total flux) and the second of 1.8×10^{-11} erg cm^{-2} s^{-1}. Further analysis of the XMM-Newton observations, including phase resolved spectroscopy, will be reported elsewhere.

3. Discussion

Our new diffraction limited VLT images of the XTE J1810−197 field, carried out six months after the previous ones, clearly show a decrease in the IR flux of the candidate previously proposed based only on positional coincidence and unusual colours (Israel et al. 2004a). This finding confirms it as the IR counterpart of XTE J1810−197, which showed during the same period a similar variation in its X-ray flux.

The only other case of correlated X-ray and IR flux variations in an AXP observed to date was found after the detection of a series of short bursts from 1E 2259+586 (Kaspi et al. 2003). In this case the X-ray and IR fluxes decreased by a factor less than two in about one week. The X-ray pulse shape, the pulsed fraction and the spectral parameters changed significantly (Woods et al. 2003), and a glitch was also observed. The X-ray and IR variability reported here for XTE J1810−197 is
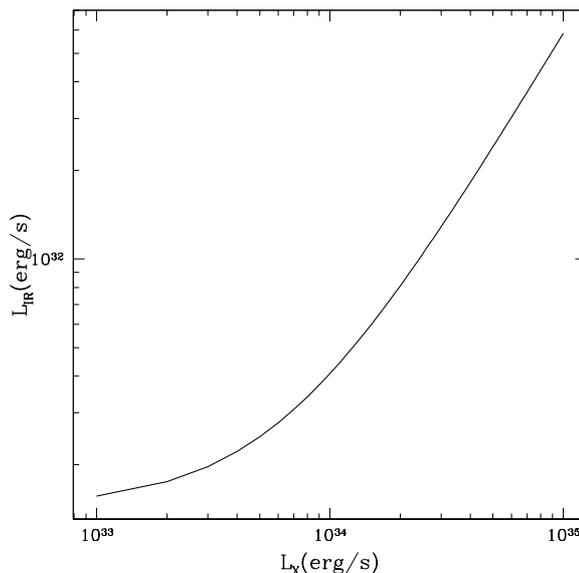
not obviously tied to bursting activity from the source (although the occurrence of bursts before the observation, or at the time of the start of the outburst between November 2002 and January 2003, cannot be excluded).

Contrary to the case of 1E 2259+586, we do not see large variations in the timing or spectral properties of XTE J1810−197 between the two XMM-Newton observations. There is only some evidence for a moderate softening of the X-ray spectrum, as indicated by the change of the photon index from 3.7 ± 0.2 (Gotthelf et al. 2004) to 4.1 ± 0.2 (for the blackbody plus power-law model fits with a constant absorption).

Comparing the X-ray outburst of XTE J1810−197 with that recently found in another AXP, 1E 1048.1−5937 (Gavriil & Kaspi 2004), we noticed that in both cases the corresponding fluences are of the order of few 10^{42} erg s^{-1}. Moreover, looking at the published decaying lightcurves for XTE J1810−197 and 1E 1048.1−5937 (Ibrahim et al. 2004; Gavriil & Kaspi 2004), it is evident the similarity of the decaying law behaviour, suggesting that both outbursts obey to the same physical process.

The IR emission from AXP in the context of the magnetar model has been recently discussed by Özel (2004), who noticed that the IR emission cannot be due to thermal emission from the neutron star surface and is consistent with synchrotron emission in the magnetosphere. The value of the IR to X-ray flux ratio we derived for XTE J1810−197, when plotted versus the neutron star spin down luminosity, does not follow the trend of the other AXPs shown in Fig. 3 of Özel (2004). However, for what concerning the other possibility proposed by Özel (2004) in which the magnetospheric emission is powered by the magnetic energy, no quantitative predictions are reported therefore we cannot exclude this possibility.

Letter to the Editor

The somehow correlated IR/X-ray fluxes of XTE J1810-197 can be accounted for in a "hybrid" model of a magnetar surrounded by a fossil disk (Eksi & Alpar 2003). The spectral characteristics of fall-back disks around isolated neutron stars were studied in detail by Perna et al. (2000) and Perna & Hernquist (2000). They considered the contribution to the emission from both viscous dissipation and reprocessing of the X-ray luminosity from the star, finding that the long wavelength emission, and in particular the IR, is dominated by reprocessing of the X-ray radiation (presumably coming from a magnetar). This immediately implies that X-ray and IR flux variations must be correlated.

We studied the extent of this correlation for an X-ray luminosity on the order of a few $\times 10^{34}$ erg s^{-1} (assuming here a distance of 5 kpc) and for a disk model as described in the references above. We found (see Fig. 3) that a variation in X-ray luminosity of the star by a factor of $\sim$2 results in a corresponding variation of the IR flux from the disk by also a factor of 2, and the intensity of the predicted IR flux is also consistent with the observations (assuming a typical 60° inclination of the disk). These results are largely independent of the inner and outer radius of the disk, as the IR emission is produced in a small ring which, for the range of X-ray luminosities under consideration is at a distance of a few $\times$ 10^{10}–10^{11} cm.

In this scenario we expect L_{IR} and L_X to be correlated, even if not linearly. This is due to the fact that, as L_X increases, the overall temperature in the disk consequently increases, and the region with temperatures at which the IR radiation is produced moves towards larger radii. This results in a larger emission area. On the other hand, as L_X decreases, the flux from the disk becomes gradually more dominated by viscous dissipation up to a point where this completely takes over and L_{IR} becomes independent of L_X: however the L_X limit value for the reprocessing dominated IR emission is largely lower than the typical AXPs X-ray luminosity, we then conclude that in the AXPs case the IR emission is almost completely due to the X-ray reprocessing phenomenon. By considering the AXPs sample as a whole, we would expect that X-ray brighter objects would generally have brighter IR counterparts. Indeed, this has been hinted at by Hulleman et al. (2004).

Our suggestion can be tested by a search for pulsations in the IR radiation similarly to the search that Kern & Martin (2002) performed in the optical.

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